Parallel Microassembly with Electrostatic Force Fields*

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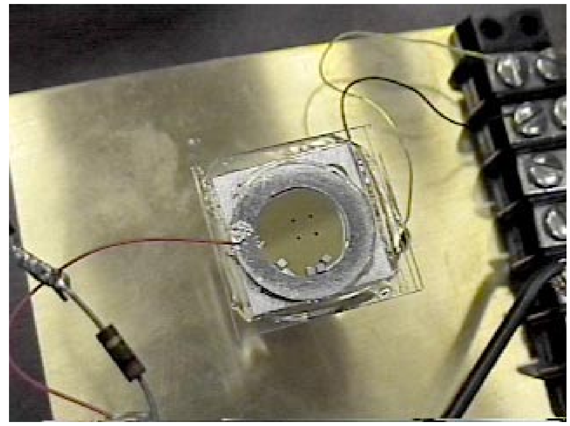
http://www.ieor.berkeley.edu/~karl/MicroSelfAssembly

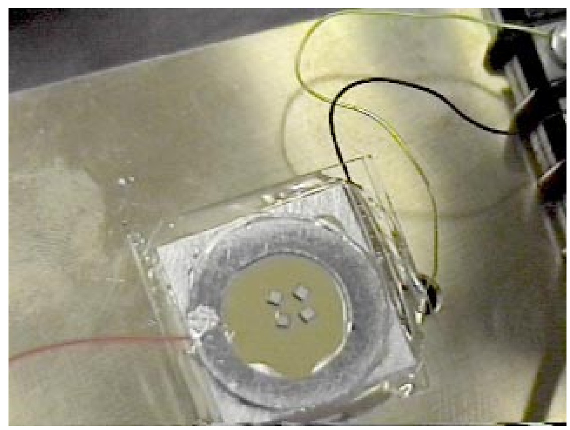
Abstract

Assembly is a fundamental issue in the volume production of products that include microscopic (submillimeter) parts. These parts are often fabricated in parallel at high density but must then be assembled into patterns with lower spatial density. In this paper we propose a new approach to microassembly using 1) ultrasonic vibration to eliminate friction and adhesion, and 2) electrostatic forces to position and align parts in parallel. We describe experiments on the dynamic and frictional properties of collections of microscopic parts under these conditions. We first demonstrate that ultrasonic vibration can be used to overcome adhesive forces; we also compare part behavior in air and vacuum. Next, we demonstrate that parts can be positioned and aligned using a combination of vibration and electrostatic forces. Finally, we demonstrate part sorting by size.

Motivated by these feasibility experiments, our goal is a systematic method for designing implementable planar force fields *for microassembly based on part geometry. Although artificial potential fields are well-known, to our knowledge this is the first attempt to systematically design physical potential fields for manipulation.*



(a)



(b)

Figure 1: Parallel microassembly with electrostatic force fields: (a) Surface-mount capacitors are placed onto a glass substrate with a 100 nm thin patterned Cr-Au electrode. Frictional and adhesive forces are overcome by ultrasonic vibration. (b) Voltage applied to the electrode creates an electrostatic field. The parts are attracted to the apertures in the electrode (dark squares) and are trapped there.

1 Introduction

Increased miniaturization of mass-produced products such as disk drives, wireless transceivers, displays, and sensors requires fundamental innovations in parts design and handling. Many of the components in these products will be integrated circuits (ICs) or micro electro mechanical systems (MEMS). These components are built using microfabrication processes derived from VLSI technology, which allows the manufacture of thousands or millions of components in par-

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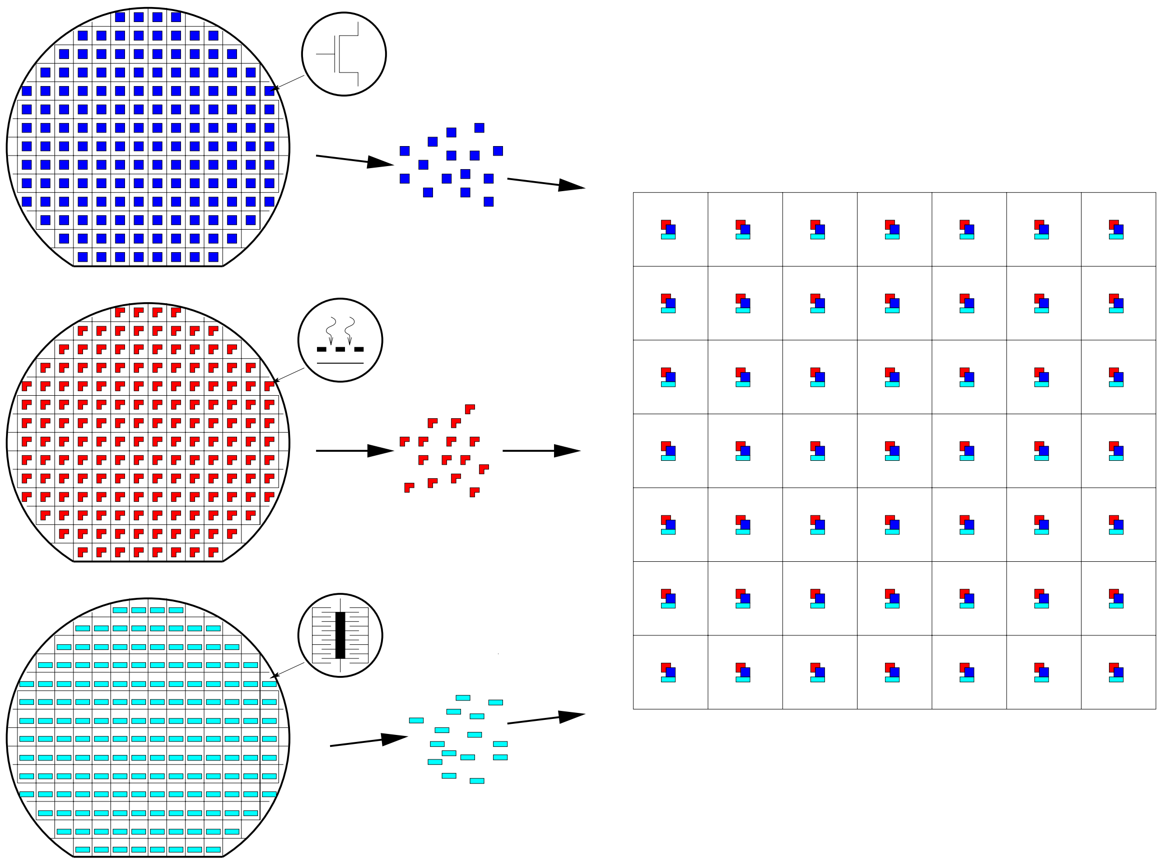


Figure 2: Parallel microassembly: Multiple micro-scale components (e.g. electronics, photonics, and MEMS) are built in parallel using standard fabrication processes. They are positioned and combined with other components on a hybrid "pallet." Note that the fabrication density is very high, while the pallets may have a larger size and lower density.

allel, in one single batch.

Current MEMS technology generally uses *monolithic* designs in which all components are fabricated in one (lengthy) sequential process. A feature of current MEMS fabrication is the wide variety of non-standard processes and materials that may be incompatible with each other. These incompatibilities severely limit the manufacture of more complex MEMS devices. Recently, microassembly has been proposed as a means to achieve *hybrid* micro-scale devices of high complexity, while maintaining high yield and low cost: various IC and MEMS components are fabricated and tested individually before being assembled into complete systems (see e.g. [7, 9, 15, 30, 31, 21, 4]).

Currently, microassembly is performed by humans with tweezers and microscopes or with high precision pick-and-place robots. Both methods are inherently serial. Since individual parts are fabricated in parallel, it is intriguing to consider how they might be *assembled* in parallel. In this paper we propose a concept for massively parallel assembly (see Figure 2).

The idea is to arrange microscopic parts on a reusable pallet and then to press two pallets together, thereby assembling the entire array in parallel. We focus on how to position and align an initially random collection of parts. Our approach to parallel feeding is analogous to Sony's APOS system for palletizing macroscopic parts; the primary difference is that we use electrostatic fields on a flat surface to align parts whereas APOS uses gravity and custom designed "pockets" [14]. Both methods avoid sensing and servoing.

This approach builds on the planning philosophy of sensorless, nonprehensile manipulation pioneered by Erdmann and Mason [10]. To model electrostatic forces acting on parts moving on a planar surface, we use the *planar force field*, an abstraction defined with piecewise continuous functions on the plane that can be locally integrated to model the motion of parts [6]. In contrast to the well-known concept of artificial potential fields, electrostatic fields are physical and thus do not require sensing or feedback.

We conjecture that planar force fields, as defined by the magnitude and direction of force at each point, can be designed to position, align and sort arrays of microscopic parts in parallel. Developing a science base for this approach requires research in device design, modeling, and algorithms.

As a feasibility study, we perform experiments to characterize the dynamic and frictional properties of microscopic parts when placed on a vibrating substrate and in electrostatic fields. We first demonstrate that ultrasonic vibration can be used to overcome friction and adhesion of small parts. In a second set of experiments, we describe how parts are accurately positioned using electrostatic traps. We are also working on methods to model part behavior as a first step toward the systematic design of planar force fields where the input is part geometry and desired final arrangement, and the output is an electrode pattern that produces the appropriate planar force field.

2 Related Work

MEMS and Micromanipulation. Over the last decade, a multitude of micro electro mechanical systems (MEMS) have been designed and built with techniques derived from VLSI processing. MEMS sensors and actuators have become commercially available, e.g. in airbag sensors or in video projection displays. Several groups of MEMS researchers have designed and built actuator arrays for micromanipulation, which usually consist of a regular grid of "motion pixels." Devices were built, among others, by Pister et al. [22], Fujita et al. [13], Böhringer et al. [6], Kovacs et al. [27, 28], and Will et al. [19, 20].

MEMS actuator arrays that implement *planar force fields* as described in the introduction were proposed by Böhringer et al. who also built single-crystal silicon actuator arrays for micromanipulation tasks [6]. Micro cilia arrays fabricated at Stanford [28] were extensively used in their experiments, which successfully demonstrated strategies for parts translating, orienting, and centering [5].

Microassembly. While earlier work on MEMS has looked almost exclusively at *in-situ* batch fabrication, interest is now shifting towards complex, assembled structures. Assembly makes possible *hybrid* devices with otherwise incompatible materials such as e.g. photoelectronic components. Assembly methods include precision robotic assembly [23], assembly based on teleoperation and visual feedback [21], flip-chip technology [8], parallel adhesion-type micro endeffectors [2], assembly with fluidic agitation [30, 31], and self assembly inspired by chemistry [29, 15].

Flip-chip technology (see e.g. [8]) allows wafer-to-wafer transfer of components fabricated in separate processes. Very high positioning accuracy is possible. However, this technique requires special artifacts such as tethers or fasteners to perform the transfer, and the structures are limited to be essentially two-dimensional.

In microassembly experiments with fluids, semiconductor junction lasers were suspended in liquid and trapped in micromachined wells on a wafer by solvent-surface forces [30, 31].

The term "self-assembly" has been applied to spontaneous ordering processes such as crystal and polymer growth. Recently it has been proposed for the manufacture of hybrid circuits and MEMS incorporating large numbers of devices (see e.g. [29, 7, 15]). Positioning, orienting, and assembly is done open-loop, without sensor feedback.

Scaling effects. It has been noted that in large scale robotics, the main problem is to pick up objects; at small scales, the main problem is to put down objects. At submillimeter scales, gravitational forces become insignificant compared to adhesive forces stemming from surface tension, Van-der-Waals forces, or electrostatic attraction. A thorough discussion of adhesion at the micro scale can be found in [12].

Vibration. Vibration is widely used in industrial parts feeders. A parts feeder is a machine that singulates, positions, and orients bulk parts before they are fed to an assembly station. Sony's APOS parts feeder ([14], see Introduction) is another example of using vibration for parts handling.

A system that does not need specialized mechanical components was presented in [3]. A transversely vibrating plate is used to systematically manipulate parts, by actively orienting and localizing them. The idea is to generate and change dynamic modes for the plate by varying the applied frequency of oscillation. Depending on the node shapes of the plate for these frequencies, the position and orientation of the parts can be controlled. Lateral vibrations were used in [25].

Vibration in fluids and gases has been used to move objects to a node in a pressure standing wave. This

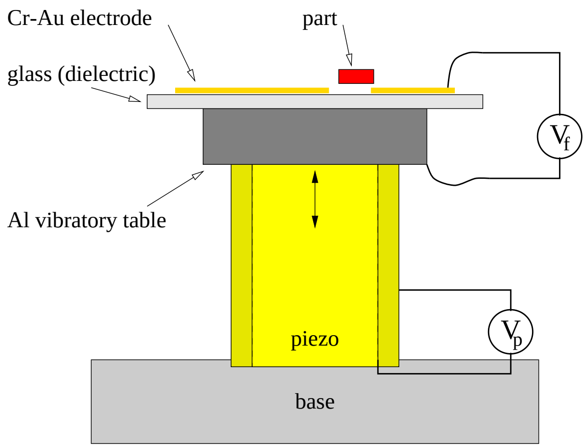


Figure 3: Experimental apparatus for self assembly with electrostatic traps. A vibratory table with a gold-covered dielectric is attached to a piezoelectric actuator. The aperture in the upper electrode creates a fringing field that causes polarization in the part. The part is attracted to the aperture.

method is called "acoustic levitation" and has been used by NASA to simulate weightlessness (see e.g. [1]).

3 Experimental Apparatus

A piezoelectric actuator supports a vibratory table consisting of a rigid aluminum base, which has a flat glass plate (25 mm × 25 mm × 2 mm) attached to its top. A thin chrome-gold layer (1000 Å) is evaporated onto the glass and patterned using photolithography. The signal from a function generator is amplified and transformed to supply the input voltage for the piezo transducer. The piezo is driven at ultrasonic frequencies in the 20 kHz range. At resonance we observe amplitudes of up to 500 nm (measured with laser interferometry), which correspond to accelerations of several hundred g's. Figure 3 shows a diagram of the experimental setup. The current experimental apparatus is shown in Figure 4. The apparatus can be operated in air or in a vacuum chamber.

Voltage is applied between the aluminum vibratory table and the chrome-gold electrode, which together act as a parallel plate capacitor. The applied voltage is limited by the breakdown voltage of air and glass and the path length (air: $3 \cdot 10^6 \frac{\mathrm{V}}{\mathrm{m}}\ 1\,\mathrm{cm} = 30\,\mathrm{kV}$; glass: $10^9 \frac{\mathrm{V}}{\mathrm{m}}\ 2\,\mathrm{mm} = 2\,\mathrm{MV}$). The patterned top electrode creates fringing electrostatic fields. Its effect is a potential field whose minima lie at apertures in the top electrode (see Figure 5). Parts are attracted to these electrostatic "traps."

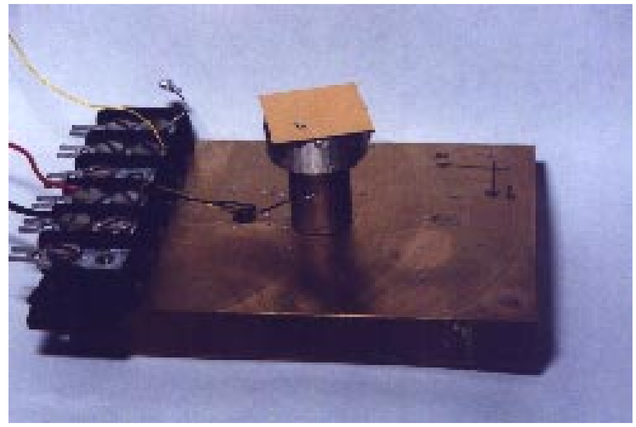


Figure 4: Experimental apparatus for self assembly experiments. A lithographically patterned electrode is attached to a piezoelectric actuator (vertical cylinder). Some parts can be seen in the lower left quadrant of the substrate.

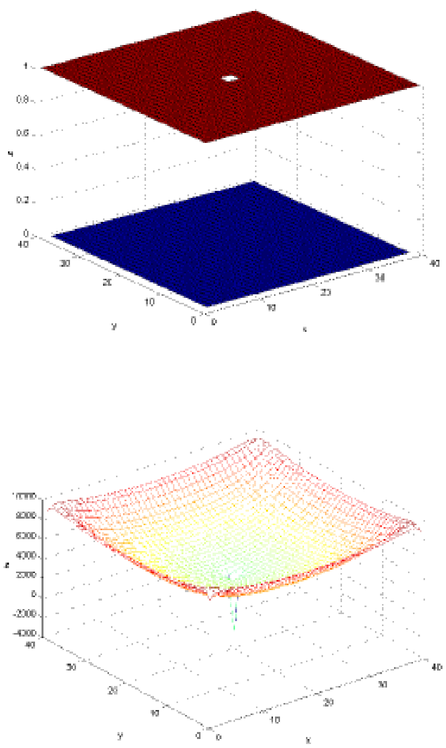
The parts employed in our experiments are mainly surface-mount diodes and capacitors. They usually have rectangular shapes with dimensions between 0.75 mm and 2 mm. We also performed experiments with short pieces of gold wire (0.25 mm diameter).

4 Experimental Observations

Overcoming Friction and Adhesion. Small parts were randomly distributed on the substrate. When no signal is applied to the piezo, the parts tend to stick to the substrate and to each other, due to static charges, capillary or Van-der-Waals forces. When applying sinusoidal signals of various frequencies and amplitude, the parts break contact. This behavior was particularly pronounced at resonance frequencies (e.g. observed in the 20 kHz range). In this case the motion of the parts resembles liquid: tilting of the substrate surface by less than 0.2 percent was sufficient to influence their direction of (down-slope) motion. This implies a friction coefficient $\mu < 0.002$.

When the substrate surface was leveled carefully, the parts exhibited random Brownian motion patterns, until they settled in a regular grid pattern. This important observation is a strong indication that the system is sufficiently sensitive to react even to very small surface forces.

At high signal amplitudes, the vibration induces random bouncing of the parts. Reducing the ampli-



(a)

(b)

Figure 5: Model of experimental setup: (a) Two parallel plates with a single aperture in the top electrode. (b) Potential field generated when voltage is applied between the plates. Note the minimum in the center of the plate which corresponds to the aperture in the top plate. This field was calculated with a finite element model.

tude accomplishes an annealing effect; at lower amplitudes only in-plane translations and rotation occurs. After such annealing sequences, surface mount diodes consistently settled with their solder bumps facing up. This observation suggests that even very small asymmetries in part design can be exploited to influence its final rest position. Voltages of $V_{pp} = 2\,\mathrm{V}$ were sufficient to sustain free motion of the parts. This corresponds to a vibration amplitude of approximately 30 nm.

Vacuum Experiments. These experiments were repeated both in air and in low vacuum (high mTorr range). First results indicate that the energy required to overcome adhesive forces decreases with pressure, probably due to squeeze film effects [11], and due to

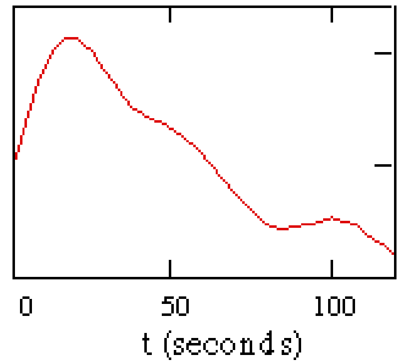


Figure 6: Histogram of binding times for electrostatic trapping, from an experiment with a total of 70 sample runs. Data exhibits an exponential distribution.

the vacuum created between the flat part bottom surface and the substrate when operated at ultrasonic frequencies. As a result, the atmospheric pressure acting on the top surface presses the part onto the surface. For example, simple calculations show that if a rectangular part with dimensions 1 mm $\times$ 1 mm $\times$ 0.1 mm and mass 0.1 mg were exposed to atmospheric pressure on one side and to vacuum on the other side, it experienced an acceleration of nearly 100,000 g.

Electrostatic Self-Assembly. The electrode design represents a parallel-plate capacitor with apertures in the upper electrode. The resulting fringing fields induce polarization in neutral parts, so that they are attracted to the apertures, and get trapped there. Once a part is trapped, it reduces the fringing field, which prevents attraction of more parts to this location. Figure 1 shows the positioning of four surface mount capacitors on four sites. The binding times for parts were automatically measured with an optical sensor and a recording oscilloscope. They exhibit an exponential distribution (Figure 6) with expected time of approximately 30 seconds.

Parts Sorting by Size. Large and small parts were mixed and placed randomly on a vibrating surface slightly tilted by $\approx 1°$. Vibration caused a sorting effect such that parts were separated with smaller parts settling at the lower end of the vibrating surface.

5 Modeling and Simulation

A variety of effects influence the behavior of the parts used in our microassembly experiments, among

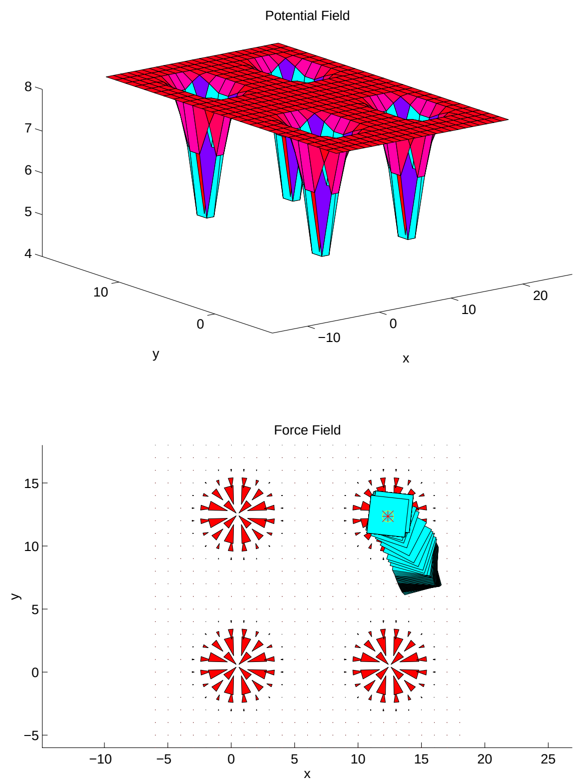


Figure 7: (a) Potential field created by an electrode with four small square-shaped apertures, as shown in the experimental setup in Figure 1. The four potential traps correspond to the four apertures. (b) Simulation of a square part moving in the corresponding force field (denoted by force vectors) The part translates and rotates until it reaches a local minimum in the potential field.

others (1) electrostatic fields created by capacitor plates, (2) conductivity or dielectric constants of parts, (3) induced dipoles, and (4) static charges on nonconductive and electrically isolated conductive parts.

Results from modeling based on a smooth approximation of the electrostatic potential are shown in Figure 7. The potential U is created by an electrode design as shown in Figure 1. The corresponding planar force field $F = \nabla U$ is shown in Figure 7(b), together with a simulation of a part moving in the field. In this simulation, the effective force on the part F_P was determined by integrating the force field over the part area $F_P = \int_P F \, dA$ (a more accurate model will take into account the deformation of the field by the part, as well as e.g. changes in its induced charge distribution). Then the force F_P is integrated over time to determine the part motion.

6 Algorithmic Issues for Massively Parallel Manipulation

As shown in the previous sections, planar force fields (PFFs) constitute a useful tool to model massively-parallel, distributed manipulation based on geometric and physical reasoning. Applications such as parts-feeding can be formulated in terms of the force fields required. Hence, planar force fields act as an abstraction between applications requiring parallel manipulation, and their implementation e.g. with MEMS or vibratory devices. Such abstractions permit hierarchical design, and allow application designs with greater independence from underlying device technology.

Recently Developed PFFs. Böhringer, Donald, et al. in [5] established the foundations of massively parallel manipulation with force fields. Among the PFFs developed in the past years the following have been thoroughly investigated:

Squeeze Field: Squeeze fields are fields with unit forces pointing perpendicularly towards a straight *squeeze line* (e.g. $\mathbf{F}(x, y) = (-\mathrm{sign}(x), 0)$). When placed in a squeeze field, every part reaches one out of a small number of possible equilibria.

Radial Field: A unit radial field is given by $\mathbf{F}(x, y) = -\frac{1}{\sqrt{(x^2+y^2)}}(x, y)$ if $(x, y) \neq 0$, and 0 otherwise. In a radial field, any polygonal part has a unique *pivot point.* The part is in a unique translational equilibrium if and only if its pivot point coincides with the center of the squeeze field.

Elliptic Field: The elliptic PFF (see Kavraki [16]) is a continuous field of the form $\mathbf{F}(x, y) = (-\alpha x, -\beta y)$, where α and β and two distinct positive constants. The field poses and orients non-symmetric parts into two stable equilibrium configurations.

Motion Planning with Artificial and Physical Potential Fields. Robotics motion planning is concerned with the problem of moving an object from an initial configuration q_i to a goal configuration q_g. In our case, a manipulation plan consists of a sequence of planar force fields. A general question that arises in the context of PFFs is the following: *Which force fields are suitable for manipulation strategies?* That is: can we characterize all those force fields in which every part has stable equilibria? To answer these questions, we use recent results from the theory of *potential fields.* It can be shown that certain PFFs that implement potential fields have this property, whereas fields without potential do not induce stable equilibria on all parts. Previous work has developed control strategies with *artificial* potential fields [17, 18, 26, 24], and discrete approximations to physical potential fields [6, 5]. The fields employed in this paper are non-artificial (i.e., *physical*). Artificial potential fields require a tight feedback loop, in which, at each clock tick, the robot senses its state and looks up a control (i.e., a vector) using a state-indexed navigation function (i.e., a vector field). In contrast, physical potential fields employ no sensing, and the motion of the manipulated object evolves open-loop (for example, like a body in a gravity field). Hence, for physical potential fields such as electrostatic fields, the motion planning problem has to be solved during device design. A design algorithm takes as input part geometry and desired goal configurations, and returns an electrode geometry that creates the proper potential field. During execution, the systems runs open-loop. We believe that this shift of complexity from run-time to design-time is crucial for efficient parallel microassembly methods.

7 Conclusions

Our experiments show that friction and adhesion between small parts can be overcome by ultrasonic vibration. In such an effectively frictionless environment, we demonstrate that small parts can be accurately positioned in parallel with electrostatic traps. This research opens the door to parallelize the manufacture of a new generation of consumer and industrial products, such as hybrid IC / MEMS devices, flat panel displays, or VCSEL arrays.

The behavior of the parts on the substrate can be modeled using planar force fields (PFFs), which describe the effective lateral force acting on the part (as a function of its location in configuration space). A key problem is to determine an electrode design that creates a specific PFF, such that parts are reliably positioned and oriented at desired locations. We attack this problem by the development of efficient models for manipulation in electrostatic force fields, and with new algorithms for motion planning with planar force fields.

We believe that planar force fields have enormous potential for precise parallel assembly of small parts. The goal of this research is to develop an entirely new methodology for precision part manipulation and to demonstrate it with new theory, algorithms, and high-performance devices. For updated information on this project see our WWW pages at `www.ieor.berkeley.edu/~karl/MicroSelfAssembly`.

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